SINGLE-MODE AMPLIFIERS AND COMPRESSORS BASED ON MULTI-MODE FIBERS

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to the use of multi-mode fibers for amplification of laser light in a single-mode amplifier system.

Description of the Related Art

Rare-earth-doped optical fibers have long been considered for use as sources of coherent light, as evidenced by U.S. Patent No. 3,808,549 to Maurer (1974), since their light-guiding properties allow the construction of uniquely simple lasers. However, early work on fiber lasers did not attract considerable attention, because no methods of generating *diffraction-limited* coherent light were known. Many current applications of lasers benefit greatly from the presence of diffraction limited light.

Only when it became possible to manufacture single-mode (SM) rare-earth-doped fibers, as reported by Poole et al. in "Fabrication of Low-Loss Optical Fibres Containing Rare-Earth Ions, *Optics Letters*, Vol. 22, pp. 737-738 (1985), did the rare-earth-doped optical fiber technology become viable. In this technique, only the fundamental mode of the optical fiber is guided at the lasing wavelength, thus ensuring a diffraction-limited output.

Driven by the needs of optical fiber telecommunications for SM optical fiber amplifiers, nearly all further developments for more than a decade in this area were concentrated on perfecting SM fiber amplifiers. In particular, the

motivation for developing SM fiber amplifiers stemmed from the fact that SM fiber amplifiers generate the least amount of noise and they are directly compatible with SM fiber optic transmission lines. SM fiber amplifiers also have the highest optical transmission bandwidths, since, due to the absence of any higher-order modes, modal dispersion is completely eliminated. In general, modal dispersion is the most detrimental effect limiting the transmission bandwidth of multi-mode (MM) optical fibers, since the higher-order modes, in general, have different propagation constants.

However, in the amplification of short-optical pulses, the use of SM optical fibers is disadvantageous, because the limited core area limits the saturation energy of the optical fiber and thus the obtainable pulse energy. The saturation energy of a laser amplifier can be expressed as

T30X

$$E_{sat} = \frac{h\nu A}{\sigma},$$

where h is Planck's constant, ν is the optical frequency, σ is the stimulated emission cross section and A is the core area. The highest pulse energy generated from a SM optical fiber to date is about 160 μJ (disclosed by Taverner et al. in *Optics Letters*, Vol. 22, pp. 378-380 (1997)), and was obtained from a SM erbium-doped fiber with a core diameter of 15 μm, which is about the largest core diameter that is compatible with SM propagation at 1.55 μm. This result was obtained with a fiber numerical aperture of

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$NA \approx 0.07$. Any further increase in core diameter requires a further lowering of the NA of the fiber and results in an unacceptably high sensitivity to bend-losses.

As an alternative to SM amplifiers, amplification in multi-mode (MM) optical fibers has been considered. See, for example, "Chirped-pulse amplification of ultrashort pulses with a multimode Tm:ZBLAN fiber upconversion amplifier" by Yang et al., *Optics Letters*, Vol. 20, pp. 1044-1046 (1995). However, in general, amplification experiments in MM optical fibers have led to non-diffraction-limited outputs as well as unacceptable pulse broadening due to modal dispersion, since the launch conditions into the MM optical fiber and mode-coupling in the MM fiber were not controlled.

It was recently suggested by Griebner et al. in "Efficient laser operation with nearly diffraction-limited output from a diode-pumped heavily Nd-doped multimode fiber", *Optics Letters*, Vol. 21, pp. 266-268 (1996), that a near diffraction-limited output beam can be obtained from a MM fiber laser when keeping the fiber length shorter than 15 mm and selectively providing a maximum amount of feedback for the fundamental mode of the optical fiber. In this technique, however, severe mode-coupling was a problem, as the employed MM fibers supported some 10,000 modes. Also, only an air-gap between the endface of the MM fiber and a laser mirror was suggested for mode-selection. Hence, only very poor modal discrimination was obtained, resulting in poor beam quality.

In U.S. Patent No. 5,187,759 to DiGiovanni et al., it was suggested that amplified spontaneous emission (ASE) in a MM fiber can be reduced by selectively exciting any active ions close to the center of the fiber core or by confining the active ions to the center of the fiber core. Since the overlap of the low-order modes in a MM optical fiber is highest with the active ions close to the center of the fiber core, any ASE will then also be predominantly generated in low-order modes of the MM fiber. As a result, the total amount of ASE can be greatly reduced in the MM fiber, since no ASE is generated in high-order modes. However, DiGiovanni described dopant confinement only with respect to ASE reduction. DiGiovanni did not suggest that, in the presence of mode-scattering, dopant confinement can enhance the beam quality of the fundamental mode of the MM fiber under SM excitation. Also, the system of DiGiovanni did not take into account the fact that gain-guiding induced by dopant confinement can in fact effectively guide a fundamental mode in a MM fiber. This further reduces ASE in MM fibers as well as allowing for SM operation.

In fact, the system of DiGiovanni et al. is not very practical, since it considers a MM signal source, which leads to a non-diffraction-limited output beam. Further, only a single cladding was considered for the doped fiber, which is disadvantageous when trying to couple high-power semiconductor lasers into the optical fibers. To couple high-power semiconductor lasers into

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MM fibers, a double-clad structure, as suggested in the above-mentioned patent to Maurer, can be of an advantage.

To the inventors' knowledge, gain-guiding has not previously been employed in optical fibers. On the other hand, gain-guiding is well known in conventional semiconductor and solid-state lasers. See, for example, "Alexandrite-laser-pumped Cr^{3+}:$LiSrAlF_6$" by Harter et al., *Optics Letters*, Vol. 17, pp. 1512-1514 (1992). Indeed, in SM fibers, gain-guiding is irrelevant due to the strong confinement of the fundamental mode by the wave-guide structure. However, in MM optical fibers, the confinement of the fundamental mode by the waveguide structure becomes comparatively weaker, allowing for gain-guiding to set in. As the core size in a MM fiber becomes larger, light propagation in the fiber structure tends to approximate free-space propagation. Thus, gain-guiding can be expected eventually to be significant, provided mode-coupling can be made sufficiently small.

In addition to providing high pulse energies, MM optical fiber amplifiers can also be used to amplify very high peak power pulses due to their increased fiber cross section compared to SM fiber amplifiers. MM undoped fibers and MM amplifier fibers can also be used for pulse compression as recently disclosed by Fermann et al. in U.S. Application No. 08/789,995 (filed January 28, 1997). However, this work was limited to the use of MM fibers as soliton Raman compressors in conjunction with a

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nonlinear spectral filtering action to clean-up the spectral profile, which may limit the overall efficiency of the system.

Compared to pulse compression in SM fibers, such as that disclosed in U.S. Patent No. 4,913,520 to Kafka et al., higher-pulse energies can be obtained in MM fibers due to the increased mode-size of the fiber. In particular, V-values higher than 2.5 and relatively high index differences between core and cladding (i.e. a $\Delta n > 0.3\%$) can be effectively employed. In "Generation of high-energy 10-fs pulses by a new pulse compression technique", Conference on Lasers and Electro-Optics, CLEO 91, paper CTuR5, Optical Society of America Technical Digest Series, #9, pp. 189-190 (1996), M. Nisoli et al. suggested the use of hollow-core fibers for pulse-compression, as hollow-core fibers allow an increase in the mode size of the fundamental mode. However, hollow-core fibers have an intrinsic transmission loss, they need to be filled with gas, and they need to be kept straight in order to minimize the transmission losses, which makes them highly impractical.

As an alternative to obtaining high-power pulses, chirped pulse amplification with chirped fiber Bragg gratings may be employed, as disclosed in U.S. Patent No. 5,499,134 to Galvanauskas et al. (1996). One of the limitations of this technique is that, in the compression grating, a SM fiber with a limited core area is employed. Higher pulse energies could be obtained by employing chirped fiber Bragg gratings in MM fibers with reduced mode-

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coupling for pulse compression. Indeed, unchirped fiber Bragg gratings were recently demonstrated in double-mode fibers by Strasser et al. in "Reflective-mode conversion with UV-induced phase gratings in two-mode fiber", *Optical Society of America Conference on Optical Fiber Communication*, OFC97, pp. 348-349, (1997). However, these gratings were blazed to allow their use as mode-converters, i.e., to couple the fundamental mode to a higher-order mode. The use of Bragg gratings in pulse-compression calls for an unblazed grating to minimize the excitation of any higher-order modes in reflection.

It has long been known that a SM signal can be coupled into a MM fiber structure and preserved for propagation lengths of 100s of meters. See, for example, "Pulse Dispersion for Single-Mode Operation of Multimode Cladded Optical Fibres", Gambling et al., *Electron. Lett.*, Vol. 10, pp. 148-149, (1974) and "Mode conversion coefficients in optical fibers", Gambling et al., *Applied Optics*, Vol. 14, pp. 1538-1542, (1975). However, Gambling et al. found low levels of mode-coupling only in liquid-core fibers. On the other hand, mode-coupling in MM solid-core fibers was found to be severe, allowing for the propagation of a fundamental mode only in mm lengths of fiber. Indeed, as with the work by Griebner et al., Gambling et al. used MM solid-core optical fibers that supported around 10,000 or more modes.

In related work, Gloge disclosed in "Optical Power Flow in Multimode Fibers", *The Bell System Technical Journal*, Vol. 51, pp. 1767-1783, (1972),

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the use of MM fibers that supported only 700 modes, where mode-coupling was sufficiently reduced to allow SM propagation over fiber lengths of 10 cm.

However, it was not shown by Gloge that mode-coupling can be reduced by operating MM fibers at long wavelengths (1.55 μm) and by reducing the total number of modes to less than 700. Also, in this work, the use of MM fibers as amplifiers and the use of the nonlinear properties of MM fibers .was not considered.

The inventors are not aware of any prior art using MM fibers to amplify SM signals where the output remains primarily in the fundamental mode, the primary reason being that amplification in MM fibers is typically not suitable for long-distance signal propagation as employed in the optical telecommunication area. The inventors are also not aware of any prior art related to pulse compression in multi-mode fibers, where the output remains in the fundamental mode.

All of the above-mentioned articles, patents and patent applications are hereby incorporated herein by reference.

SUMMARY OF THE INVENTION

It is an object of the present invention to increase the energy storage potential in an optical fiber amplifier and to produce peak powers and pulse energies which are higher than those achievable in single-mode (SM) fibers before the onset of undesirable nonlinearities and gain saturation.

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Another object of the present invention is to achieve amplification of the fundamental mode within a multi-mode (MM) fiber while reducing amplified spontaneous emission (ASE).

A further object of the present invention is to employ gain-guiding within a MM fiber to improve the stability of the fundamental mode.

Yet another object of the present invention is to compress high peak power pulses into the range of a few psec to a fsec while preserving a near diffraction-limited output.

To achieve the above objects, the present invention employs a multi-mode (MM) optical fiber in an optical amplification system. According to the present invention, MM optical fibers, *i.e.*, fibers with a V-value greater than approximately 2.5, provide an output in the fundamental mode. This allows the generation of much higher peak powers and pulse energies compared to SM fibers before the onset of undesirable nonlinearities and gain saturation. The increased fiber cross section equally greatly increases the energy storage potential in an optical fiber amplifier. The amplification system of the present invention is useful in applications requiring ultrafast and high-power pulse sources.

According to one aspect of the present invention, the gain medium is in the center of the MM fiber so that the fundamental mode is preferentially amplified and spontaneous emission is reduced. Further, gain-confinement is

used to stabilize the fundamental mode in a fiber with a large cross section by gain guiding.

According to one embodiment of the present invention, the exploitation of self-phase modulation and other nonlinearities in (rare-earth) doped or undoped MM fibers allows the compression of high peak power pulses into the range of a few fsec while a near diffraction-limited output is preserved.

According to another embodiment of the present invention, by writing chirped fiber Bragg gratings into MM optical fibers with reduced mode-coupling, the power limits for linear pulse compression of high-power optical pulses are greatly increased. Further, by employing double-clad MM fiber amplifiers, pumping with relatively large-area high-power semiconductor lasers is made possible.

According to yet another embodiment of the present invention, the incorporation of efficient mode-filters enables cw lasing in a near diffraction-limited single mode from (rare-earth) doped MM optical fibers.

According to yet another embodiment of the present invention, MM optical fibers allow the construction of fiber optic regenerative amplifiers and high-power Q-switched lasers. Further, MM optical fibers allow the design of cladding-pumped fiber lasers using dopants with relatively weak absorption cross sections.

These and other objects and features of the present invention will be apparent from the following detailed description of the preferred embodiments and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagrammatic view of a multi-mode fiber amplifier system according to the first embodiment of the present invention.

Fig. 2 is a graph showing the coupling efficiency of a multi-mode amplifier fiber into a mode-filter fiber as a function of bend-radius of the multi-mode amplifier fiber.

Fig. 3 is a graph showing the autocorrelation of the amplified pulses from a multi-mode amplifier fiber measured under optimum mode-match conditions.

Fig. 4 is a graph showing the autocorrelation of the amplified pulses from a multi-mode amplifier fiber measured under non-optimum mode-match conditions.

Fig. 5 is a block diagram of a multi-mode fiber amplifier system according to the second embodiment of the present invention.

Fig. 6 is a block diagram of a multi-mode fiber amplifier system according to the third embodiment of the present invention, wherein a pulse compressor is disposed at an output of the multi-mode fiber.

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Fig. 7 is a diagrammatic view of a multi-mode fiber amplifier system according to a fourth embodiment of the present invention.

Fig. 8 is a conceptual drawing of a fiber cross section employing a doped multi-mode fiber core and an undoped fiber cladding according to a fifth embodiment of the present invention.

Fig. 9 is a diagrammatic view of a multi-mode fiber amplifier system according to a sixth embodiment of the present invention, wherein a fiber regenerative amplifier is constructed from a multi-mode fiber amplifier.

Fig. 10 is a diagrammatic view of a multi-mode fiber amplifier system according to a seventh embodiment of the present invention, wherein a MM Q-switched fiber laser source is constructed.

Fig. 11 is a block diagram of a multi-mode fiber amplifier system according to the eighth embodiment of the present invention, wherein a pre-amplifier is inserted before the multi-mode fiber.

Fig. 12 is a block diagram of a multi-mode fiber amplifier system according to the ninth embodiment of the present invention, wherein a frequency converter is disposed at an output of the multi-mode fiber.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1 illustrates an amplifier system according to a first embodiment of the present invention. In the example shown in Fig. 1, a femtosecond single-mode (SM) fiber oscillator 10, such as an erbium fiber oscillator, is

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coupled into a multi-mode (MM) fiber amplifier 12, such as an erbium/ytterbium fiber amplifier. Other examples of suitable MM fiber amplifiers include those doped with Er, Yb, Nd, Tm, Pr or Ho ions. Oscillators suitable for use in this system are described in the above-mentioned U.S. Patent Application No. 08/789,995 to Fermann et al.

A two-lens telescope 14 (L1 and L2) is used to match the mode from the oscillator 10 to the fundamental mode of the MM amplifier 12. In addition, the output of the pumped MM fiber 12 is imaged into a second SM fiber (mode-filter (MF) fiber 16 in Fig. 1) using lenses L3 and L4. Lenses L3 and L5 and beamsplitter 18 are used to couple the pump light from pump source 20 into the amplifier fiber, as described below.

In one example of the system arranged according to Fig. 1, the oscillator 10 delivers 300 fsec near bandwidth-limited pulses at a repetition rate of 100 MHz at a wavelength of 1.56 μm with a power level of 14 mW.

The amplifier fiber 12 can be, for example, a double-clad MM erbium/ytterbium amplifier with a core diameter of ≈ 28 μm and a core numerical aperture of NA = 0.19. The inner cladding in this example has a diameter of ≈ 220 μm and a numerical aperture of NA = 0.24. The core is located in the center of the inner cladding. The length of the amplifier is 1.10 m.

To increase the number of propagating modes in the MM amplifier 12 and for testing purposes, shorter wavelengths such as 780 and 633 nm were

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also used. In this, a femtosecond laser source operating at 780 nm and a cw laser source at 633 nm can be launched into the MM amplifier fiber 12. The MF fiber 16 can then be replaced with a fiber with a core diameter of 4 μm to ensure SM operation at these two wavelengths.

The approximate number of modes in the MM amplifier is calculated from its V-value.

T150X

$$V = \frac{2\pi a}{\lambda} NA, \qquad number\ of\ modes = \frac{1}{2}V^2 \qquad (1)$$

where a is the core radius and λ is the signal wavelength. The V-value at 1.55 μm is thus $V \approx 10.8$, and the number of modes is hence calculated as $\approx$ 58 for the above example. Typically, a fiber is considered MM when the V-value exceeds 2.41, i.e., when modes in addition to the fundamental mode can propagate in the optical fiber.

For equal excitation of N modes of a MM fiber supporting N modes the maximum coupling efficiency into a SM fiber is given approximately by

$$\eta \approx (\theta_0/\theta_{max})^2 \approx 1/N, \qquad (2)$$

where $\theta_0 \approx \lambda/4a$ is the divergence half-angle of the fundamental mode of the MM fiber. θ_{max} is the maximum divergence half-angle of the outer-most modes of the MM fiber. It is assumed that the output from the MM fiber is linearly polarized which is an appropriate assumption for the excitation of the

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lowest order modes in the fiber. Under SM excitation of the MM fiber and in the absence of mode-coupling, $\theta_{max}(z)=\theta_0$ independent of fiber length. However, in the presence of mode-coupling θ_{max} will increase, and, as a result, the possible coupling efficiency from the output of the MM fiber into a SM fiber will decrease as $\eta(z)=(\theta_0/\theta_{max}(z))^2$. Using the above-mentioned work by Gloge, $\eta(z)$ can be written as:

T160X

$$\eta(z)=\frac{\theta_0^2}{4Dz+\theta_0^2}. \qquad (3)$$

where D is the mode-coupling coefficient as defined by Gloge. Thus, a measurement of $\eta(z)$ gives the mode-coupling coefficient D. Equally, from equation (2), a measurement of η gives the approximate number of excited modes of a MM fiber. It is instructive to relate N to the M^2-value that is typically used to characterize the quality of near-diffraction-limited optical beams. It may be shown that $N\approx\sqrt{M^2}$. According to the present invention, a low level of mode-coupling is desirable, so that the amplified beam provided at the output of the MM fiber amplifier 12 is substantially in the fundamental mode. Accordingly, an M^2-value less than 10 is desirable, with an M^2-value less than 4 being preferable, and an M^2-value less than 2 being more preferable. Further, the number of modes is preferably in the range of 3 to 3000 and more preferably in the range of 3 to 1000.

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Mode-coupling was measured in a 1.1 m length of unpumped amplifier fiber for the above-described erbium/ytterbium fiber (fiber 1), and three commercially available MM-fibers (fiber 2, 3 and 4). The fiber parameters and the mode-coupling coefficient D (in m^{-1}) of these fibers are shown in Table 1. Fibers 1, 3 and 4 are made by the MCVD process; fiber 2 is made by a rod-in-tube technique.

T170X

Table 1

	fiber 1	fiber 2	fiber 3	fiber 4
NA	0.19	0.36	0.13	0.13
core diameter (μm)	28	50	50	50
cladding diameter (μm)	200	125	125	250
number of modes at 1.55 μm	58	665	87	87
number of modes at 0.79 μm	223			
number of modes at 0.63 μm	350			
$D(m^{-1})$ at 1.55 μm	$<2x10^{-6}$	$8x10^{-4}$	$8x10^{-5}$	$7x10^{-6}$
$D(m^{-1})$ at 0.79 μm	$4x10^{-6}$			
$D(m^{-1})$ at 0.63 μm	$2x10^{-5}$			
L_b(mm) at 1.55 μm	1.9	5.3	5.7	5.7
L_b(mm) at 0.79 μm	3.3			
L_b(mm) at 0.63 μm	4.1			
M^2(1m) at 1.55 μm	1.0	200	5.4	1.25
M^2(1m) at 0.79 μm	1.2			
M^2(1m) at 0.63 μm	2.6			

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The coupling coefficients allow, in turn, the calculation of the expected M^2 value. In this example, the calculated M^2-values were produced after propagation through 1m of MM fiber 12. For fiber 1, a good agreement between the calculated and separately measured M^2-values was obtained.

The beat length L_b between the fundamental LP_{01} and the next higher-order LP_{11} mode is also given in Table 1. The beat length L_b is defined as the length it takes for the two modes to accumulate a differential phase-shift of 2π along the propagation direction. Assuming a constant scattering power spectrum, for a fixed wavelength, D can be shown to be proportional to L_b^4.

See: D. Marcuse, "The Theory of Dielectric Optical Waveguides", p. 238, Academic Press (1974); Gloge. The longer the beat length, the closer the modes are to being phase-matched and the more power will couple as a function of length. Since, as disclosed by Gloge, mode-coupling is expected to be largest between adjacent modes, it is desirable to use LP_{01}/LP_{11} beat lengths as short as possible to avoid mode-coupling.

In general, high levels of mode-coupling can be expected from fibers with high scattering loss. This suggests the possibility of low mode-coupling coefficients at long wavelengths in fibers with low scattering loss. As can be seen from Table 1, a dramatic reduction of mode-coupling occurs with increased wavelength in fiber 1. An acceptable level of mode-coupling is achieved in fiber 1 down to wavelengths as short as 790 nm. Since the

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number of modes of an optical fiber depends only on the ratio a/λ, a fiber similar to fiber 1 with a core diameter as large as 56 μm can produce acceptable levels of mode-coupling in a 1 m length. Due to the reduction of scattering at longer wavelengths, even larger core diameters are acceptable at longer wavelengths. For example, a MM fiber with a core diameter of 60 μm can amplify pulses with a peak power 16 times larger than possible with SM amplifiers described by Taverner et al. Indeed, acceptable levels of mode coupling were obtained for a specifically designed fiber with a 50 μm core diameter as evident from Table 1 and explained in the following.

Further, it is clear that, to minimize mode-coupling, step-index MM fibers are more useful than graded-index MM fibers, since the propagation constants in graded-index fibers are very similar, which greatly increases their sensitivity to mode coupling. To minimize mode-coupling, the difference in the propagation constants between fiber modes is preferably maximized.

Fiber 2 was manufactured by a rod-in-tube technique with intrinsic high scattering losses leading to much larger mode-coupling coefficients compared to the MCVD-grown fibers 1, 3 and 4. Also, the mode-coupling coefficients measured in fiber 2 are similar to results obtained by Gambling et al. and Griebner et al., who also used step-index solid-core fibers manufactured by rod-in-tube techniques. As a consequence, reduced mode-coupling can be expected from directly grown MM fibers employing, for example, MCVD, OVD, PCVD or VAD fiber fabrication techniques.

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As shown in Table 1, the mode-coupling coefficients obtained in fiber 4 at 1.55 μm are about a factor of 11 smaller than in fiber 3. This difference is explained by the fact that the outside diameter of fiber 4 is 250 μm, whereas the outside diameter of fiber 3 is 125 μm. In general, a thicker fiber is stiffer and less sensitive to bend and micro-bend induced mode-coupling, as evident from Table 1.

In experiments conducted by the inventors, the lowest mode-coupling coefficients were obtained by longitudinally stretching the optical fibers. For, example, the mode-scattering coefficients of fiber 2 and 3 were measured while keeping the fiber under tension and while keeping the fiber straight. The application of tension in short lengths of fibers can be useful in obtaining the best possible mode-quality.

Mode-coupling was also measured in a configuration where the amplifier fiber (fiber 1) was pumped, as shown in Fig. 1. Specifically, the amplifier was pumped at a wavelength of 980 nm contra-directionally with respect to the signal with a launched power up to 3 W from a broad-stripe semiconductor laser with an active area of 1x500 μm, where demagnification was employed to optimize the power coupling into the inner cladding of the MM amplifier fiber. The amplifier was cleaved at an angle of about 8° to eliminate spurious feedback. A signal power up to 100 mW was then extracted from the amplifier system at 1.56 μm.

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The coupling efficiency of the MM amplifier fiber 12 into the MF fiber 16 as a function of bend-radius of the MM amplifier fiber 12 is shown in Fig. 2. For a straight MM amplifier fiber and for a bend-radius of 10 cm, a coupling efficiency up to 94% is obtained into the MF fiber 16, demonstrating that mode-coupling is nearly completely absent in the MM amplifier fiber 12 and that a SM can indeed propagate over lengths of several meters in such fibers. No clear onset of mode-coupling is visible even for a bend-radius of 5 cm, since, even in this case, a coupling efficiency of about 90% from the MM amplifier fiber 12 to the MF fiber 16 is obtained.

Since the measured coupling efficiencies from the MM amplifier 12 to a SM fiber are nearly the same under unpumped and pumped conditions, it is evident that gain-guiding is relatively weak in this particular amplifier fiber. This observation was also verified by a simple computer model (see below). However, clearly any dopant confinement in the center of the MM amplifier core will predominantly lead to amplification of the fundamental mode. Any light scattered into higher-order modes will experience less gain and, due to the reduced intensity overlap of the higher-order modes with the fundamental mode, low levels of scattered light in higher-order modes will also not saturate the gain of the fundamental mode. Thus, while in the above-described experimental example, the mode-scattering coefficients were so low that any effects due to gain-guiding were not readily observable, in general, gain-guiding plays a role in a MM amplifier system according to the present

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invention. In addition, the above-mentioned computer model predicts the onset of gain-guiding of the fundamental mode in MM fibers with larger core diameter and/or reduced refractive index differences between the core and cladding.

As the mode diameter increases, the size of the SM can be determined by the gain profile under small signal conditions, i.e. in the absence of gain saturation. This allows a length-dependent mode size. Initially, under small signal conditions, the mode is confined by gain-guiding. As the gain saturates, gain guiding becomes less relevant and the mode size can increase, limited eventually by the core of the MM fiber. A length-dependent mode size can also be achieved by employing a core size which tapers along the fiber length. This can, for example, be achieved by tapering the outside fiber diameter along the fiber length.

In the presence of gain-guiding, amplified spontaneous emission (ASE) is reduced, as the MM fiber essentially becomes SM. In the presence of gain-guiding, ASE is also guided predominantly in the fundamental mode, rather than in all possible modes of the MM fiber, leading to an improvement in the noise properties of the MM fiber.

Equally, in the experimental example, dopant-confinement was observed to lead to a significant reduction in the amplified spontaneous emission (ASE) levels in the fiber. This was verified by measuring the coupling efficiency of the ASE from the MM amplifier 12 into the MF fiber

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16. In this case, no signal light was coupled into the MM amplifier fiber 12. For an ASE power level of 1mW, a coupling efficiency as high as 15% was measured. A comparison with equation (2) indicates that ASE is generated mainly in about 13 low-order modes (here a factor of two from polarization degeneracy is accounted for), *i.e.*, ASE is generated in only about 20% of the total mode-volume of the amplifier fiber. The large reduction in ASE which was observed not only reduces the noise level in the amplifier; low levels of ASE also allow a reduction of the signal power that is required to saturate the amplifier. To extract the highest energy from an oscillator-amplifier signal pulse source, an operation of the amplifier in saturation is generally preferred.

The coupling efficiency at 1.55 μm and at 780 nm from the MM amplifier fiber 12 to the MF fiber 16 was not found to vary when applying small mechanical perturbations to the optical fiber. In a practical optical system, the applied mechanical perturbations are small compared to the perturbations inflicted by a 5 cm bend radius, which indicates that long-term stability of the mode-propagation pattern in such fibers can be achieved.

The MM amplifier 12 is polarization preserving for bend-radii as small as 10 cm. To obtain a high-degree of polarization holding, elliptical fiber cores or thermal stresses can be used in such fibers.

The autocorrelation of the amplified pulses from the MM amplifier fiber 12 (bend radius = 10 cm) measured under the condition of optimum mode-match and a condition of non-optimum mode-match are respectively

shown in Figs. 3 and 4. Under non-optimum mode-match, the autocorrelation displays several peaks due to the excitation of higher-order modes, which have different propagation constants. However, under optimum mode-matching conditions, any secondary peaks are suppressed to better than 1%, which indicates the high-quality of the pulses emerging from the MM amplifier fiber.

In general, the spectrum of the pulses measured at the output of the MM amplifier fiber 12 is more critically dependent on the coupling conditions than the autocorrelation. The reason for this is that the spectral measurement is sensitive to the phase between the fundamental mode and the higher-order modes, *i.e.*, an energy content of higher-order modes of only 1% in the output of the MM fiber leads to a perturbation of the shape of the spectrum by 10%.

Fig. 5 is a block diagram of a multi-mode fiber amplifier system according to a second embodiment of the present invention. The system includes a near-diffraction limited input beam, a mode-converter 50 and a MM fiber amplifier 52. The near-diffraction limited input beam can be generated from any laser system, which need not be a fiber laser. The near-diffraction limited input beam can contain cw or pulsed radiation. The mode-converter 50 can consist of any type of optical imaging system capable of matching the mode of the MM amplifier 52. For example, a lens system may be employed. Alternatively, a section of tapered fiber may be employed, such that the output mode at the end of the tapered fiber is matched to the mode of the MM amplifier fiber 52. In this case, the mode-converter can be spliced directly to

the MM fiber 52 producing a very compact set-up. Any pumping configuration could be employed for the MM amplifier fiber, such as contra- or co-directional pumping with respect to the signal or side-pumping. Equally, the NA of the pump light could be reduced to minimize ASE. In this case, the use of just a single-clad fiber is more advantageous, where the pump light is directed into the fiber core. In general, the MM amplifier 52 can have a single, double or multiple cladding.

In the case of co-directional pumping, the pump light and the signal light are launched via a dichroic beamsplitter (not shown). The coupling optics are then optimized to simultaneously optimize the coupling of the pump beam and the signal beam.

A single or a double pass of the signal through the MM fiber 52 is most convenient. In the case of a double-pass configuration, a Faraday rotator mirror can be employed to eliminate polarization drifts in the system. Of course, in a double-pass configuration, after the first pass through the amplifier the coupling of the signal into higher-order modes must be avoided to ensure a near-diffraction limited output.

Optionally, linear or nonlinear optical elements can be used at the output of the system. Such a system is compatible with any application that has been used in conjunction with conventional laser systems.

Many nonlinear applications indeed require high peak pulse powers for their efficient operation, which are very difficult to achieve in cladding-

pumped SM amplifiers due to the 10s of meters of fiber length that are typically employed in such systems. Even in standard SM optical amplifiers, peak powers greater than 1 kW/amplifier length can rarely be achieved. In contrast, peak powers of $\approx$ 15 kW are achievable in a 1.5 m length of double-clad Er/Yb fiber (fiber 1 from Table 1) without appreciable non-linear effects, *i.e.*, peak powers greater than 20 kW/amplifier length can be achieved.

According to the present invention, the use of a MM amplifier is beneficial not only by way of allowing the use of a large core diameter; the use of a MM amplifier also allows a reduction of the ratio cladding/doped core diameter, which minimizes the amplifier length and thus the amplifier non-linearity. However, this leads to the generation of more ASE noise.

Fig. 6 is a block diagram illustrating a multi-mode fiber amplifier system according to a third embodiment of the present invention. In the system of the third embodiment, high-power optical pulses can be propagated (or amplified) in undoped (or amplifier) MM fibers, such that spectral broadening is obtained to allow for pulse compression of the amplifier output. For applications in nonlinear pulse-compression, optical fibers with either positive (non-soliton-supporting) or negative (soliton-supporting) dispersion can be employed. The power levels in the multi-mode fiber 60 are raised to obtain an appreciable amount of self-phase modulation. The interplay of

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dispersion and self-phase modulation in the optical fiber can then be used to broaden the spectrum of the optical pulses and to obtain pulse compression.

When the MM fiber 60 is soliton supporting, higher-order soliton compression may be used to produce short pulses from the MM fiber 60 directly. In general, in the case of positive dispersion (non-soliton supporting) fiber, additional linear or nonlinear pulse-compression components must be used to compress the spectrally broadened optical pulses. In this case, a conventional linear pulse compressor 62 (such as a prism, grating, grism or SM chirped fiber Bragg grating) may be used at the output of the system. Also, chirped periodically poled doubling crystals may be used to obtain a compressed, frequency-doubled pulse. Equally, chirped fiber Bragg gratings may be written into the MM optical fiber 60 with reduced mode-coupling to reduce the nonlinearities of such structures when applied to linear pulse compressor 62. The Bragg grating should not be blazed to eliminate the excitation of higher-order modes in reflection.

Fig. 7 is a diagrammatic view of a system according to a fourth embodiment of the present invention. As shown in Fig. 7, a mode-filter 70 is inserted in front of one of the cavity mirrors M1 and M2 to ensure a diffraction-limited output of the system. The mode filter 70 can consist of a standard SM fiber in conjunction with appropriate mode-matching optics. Alternatively, a tapered fiber can be used (as discussed above) to provide for mode-matching. For optimum mode-coupling the efficiency of the laser will

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be nearly as high as for an all-SM laser. However, the use of MM amplifier 76 allows for increased design flexibility. Thus, double-clad erbium/ytterbium fibers with different core-cladding ratios can be employed wherever appropriate.

According to a fifth embodiment, the use of MM fiber allows the design of double-clad fibers with low absorption cross sections. For example, a double-clad Er-doped amplifier fiber may be constructed from MM fibers. Typically Er-doped double-clad fibers are relatively inefficient, since large cladding/core ratios have to be employed in order to absorb pump light from broad area diode lasers while still preserving a SM fiber core. Typically, such a design would involve a $\Phi_{cl}=100$ μm diameter cladding and a $\Phi_{co}=10$ μm diameter core. The effective absorption of such a structure is 100 times $(=\Phi_{cl}/\Phi_{co})^2$ smaller than the absorption in a single-clad Er-doped fiber. Thus, 100 times longer fiber amplifier lengths are required in this case. However, by implementing MM Er-doped fiber, the core size can be greatly increased, producing much smaller cladding/core ratios and shorter amplifier lengths which is very beneficial for the design of high-power lasers. Of course, for the design of high-power Er double-clad lasers, cladding diameters even larger than 100 μm can be implemented. A conceptual drawing of a fiber cross section employing a doped MM fiber core and an undoped fiber cladding is shown in Fig. 8. As shown in Fig. 8, the active dopant is confined in a cross section, defined by the dopant profile, substantially smaller than the fiber

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core, as defined by the refractive index profile. Of course, in such laser system, dopant confinement increases the amplifier length, thus only relatively weak doping confinement is useful.

According to a sixth embodiment of the present invention, as shown in Fig. 9, a fiber regenerative amplifier may be constructed from a MM fiber amplifier 90. A regenerative amplifier is useful for obtaining mJ energies from MM fiber amplifiers. Due to the limited gain of MM fiber amplifiers, the extraction of mJ energies will typically require several passes through the amplifier, which is facilitated by the regenerative amplifier. As shown in Fig. 9, a fast optical switch (OS) 92 is used to switch the pulses in and out of the regenerative amplifier. A mode-filter 94 can also be included to "clean-up" the fiber mode in the amplification process. The mode-filter 94 can consist of a spatial filter to minimize any nonlinearities in the regenerative amplifier.

The seed pulse is selected from the oscillator 96 by the optical switch 92 at the desired repetition rate. The Faraday rotator 98 and the polarization beam splitter 99 are used to couple the amplified pulse out of the system. Either cw or pulsed pumping of the amplifier can be employed.

According to a seventh embodiment of the present invention shown in Fig. 10, a MM Q-switched fiber laser source is constructed. The large cross-sections possible with MM fibers allow greatly increasing the energy storage compared to a single-mode fiber. As a result, high-power Q-switched pulses may be directly generated from such a system. Typically, these pulses have

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a duration in the nsec regime. As shown in Fig. 10, a mode-filter 100 can also be included to ensure an optimum mode-quality. The optical switch 102 is employed for output coupling and it also serves to modulate the loss (Q) of the cavity defined by the two mirrors M1 and M2 and the MM amplifier 104. Alternatively, the output can be extracted by using a partially transmissive mirror M2.

According to an eighth embodiment of the present invention shown in Fig. 11, a preamplifier is included in front of the final MM amplifier fiber 112 to fully saturate the MM amplifier fiber 112 and to reduce the level of ASE in the MM amplifier fiber 112. The preamplifier can be SM and also MM, where it is useful to select the core radius of the preamplifier fiber 110 to be smaller than the core radius of the final MM amplifier fiber 112 to minimize the growth of ASE. One isolator (not shown) can be inserted between the laser source and the preamplifier and another isolator (not shown) can be inserted between the preamplifier 110 and the final MM amplifier fiber 112 further to reduce ASE. Similarly, narrow band optical filters (not shown) can be included anywhere in the system to reduce ASE. Also, optical switches (not shown) can be used in between the laser source, the preamplifier 110 and the final amplifier 112 to reduce the amount of ASE.

More than one preamplifier can be used in the system, where isolators and optical filters and optical switches can be used to minimize the amount of

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generated ASE in the system. Further, nonlinear processes in the preamplifiers and the final MM amplifier can be used for pulse compression.

According to a ninth embodiment of the present invention shown in Fig. 12, a frequency converter 120 is included downstream of the MM amplifier fiber 122 to frequency convert the output amplified beam. The frequency converter can be a non-linear crystal, such as a periodically-poled or aperiodically poled $LiNbO_3$ crystal which frequency doubles the output beam.

Although several exemplary embodiments have been herein shown and described, those of skill in the art will recognize that many modifications and variations are possible without departing from the spirit and scope of the invention, and it is intended to measure the invention only by the appended claims.

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